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JET VANE CONTROL SYSTEM PROTOTYPE HARDWARE DEVELOPMENT FOR THE EVOLVED SEASPARROW MISSILE

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Abstract

Rapid response to a high-speed, low-altitude, incoming missile imposes very stringent design requirements upon an air-defense missile. A successful solution has been devised by using a Jet-Vane Control (JVC) System for rapid launch maneuvering, minimizing weight penalties by using actuation elements of other missile components and making the jet-vane assembly detachable. A JVC System and method is illustrated for a surface air defense missile in which the system is compact, rugged, lightweight, and detachably connected to the aft end of a missile, adjacent to the rocket motor nozzle for the purpose of generating maneuvering forces from vanes inserted into the propellant stream. The JVC provides for very quick pitch over and roll control during shipboard vertical launch. The JVC then detaches from the missile and falls away so as not to degrade the rocket motor specific impulse during missile flight to target. There are four vanes mounted at right angles to each other, each having its own mounting support and geartrain assembly. Each vane is connected through a detachable coupling to the Steering Control System (SCS) of the missile, such that actuation of the SCS simultaneously actuates the JVC System. The Evolved Sea Sparrow Missile (ESSM) Consortium primed by Raytheon Missile Systems (RMS), and partnered with British Aerospace (BAe) Systems in the SCS Integrated Product Team (IPT) successfully designed, analyzed, prototype developed and flight tested a Thrust Vector Control (TVC) System, based on the JVC concept for immediate incorporation into the current Engineering Manufacturing Development (EMD) effort. Empirical test data collected was found to correlate well with the analytical techniques used to predict vane performance parameters. The resultant TVC System was proven to be robust and capable of meeting the ESSM operational requirements with margin.

Introduction

The mission of missile defense requires that a defensive missile be launched in the direct line of attack after a very short warning time since the incoming missile may come from any direction and at any altitude, frequently very low altitude. A mechanical launcher that directs the defense missile in the correct direction is feasible in principle but carries response time penalties. A more appropriate system is vertical launch and re-direction of the in-flight defensive missile, but this presents difficulties when the incoming missile is at very low altitude. Rapid transition from vertical to sea-level flight is at the heart of the present ESSM JVC design.

ESSM is an RMS led, international cooperative development of a sea-launched anti-missile system which successfully addresses this difficult mission. It is an upgrade of the highly successful, widely deployed RIM 7 SeaSparrow Missile. Loaded in a 'Quadpack' Canister for the Mark 41 Vertical Launch System (VLS), or in a trainable Mark 29 and vertical Mark 48 single pack launcher, this tail-controlled missile with JVC and its quick start Guidance Section offers a significant increase in load out, response time and fire power for the NATO SeaSparrow Consortium navies. Compatible with the NATO Mark 91, the Dutch Cluster IV configuration, the Anzac, and Aegis weapon systems, the versatile ESSM will readily integrate with a broad range of ship platforms and fire control systems. Figure 1 illustrates an ESSM with a tail mounted JVC aft of the SCS in a Mark 25 Quadpack Canister, and tabulates top level technical specifications.

ESSM is primarily designed to protect allied fleets and commerce shipping from air breathing threats. Offensive missiles such as cruise missiles are constructed to fly at low altitudes, just above treetops or water surfaces, to avoid detection by enemy radar. In such situations a targeted ship may have just a few seconds to first identify the threat and then take countermeasures such as firing one of its defensive missiles. In conventional designs, a ship borne defensive missile is launched from a canister or missile launcher in a vertical direction, and it must first achieve sufficient velocity before its airfoil surfaces are able to

effect any substantial maneuvers. But this means that the missile has to reach an altitude of thousands of feet before it is able to pitch over and begin seeking the incoming missile threat. The time needed for these maneuvers is now considered to be too long for effective defense against modern cruise missiles.

The major design rationale for incorporating a TVC System (of which a JVC is just one concept), onto an ESSM airframe is to allow the missile to maneuver itself immediately after launch to intercept low flying, enemy cruise missiles. A hard Pitch-Over Maneuver (POM) after missile egress is necessary to properly align the flight vehicle for the most direct propelled flight route to the target. Aerodynamic control at launch by fin stabilizers is inadequate due to low vehicle velocities, therefore rocket plume deflection by the TVC is required. Figure 2 compares flight trajectories necessary to intercept low altitude or ground targets resulting from a standard ballistic launch verses one incorporating a launch POM as assumed for a TVC equipped missile. The ballistic launch trajectory is obviously inefficient, time consuming, and limits the missile sensor Line-of-Sight (LOS) capabilities for optimum target detection and tracking. Range and time to target will be greatly enhanced with a TVC equipped interceptor missile.

Previous Studies

A number of TVC systems have previously been developed in an attempt to address this problem (References 1-6). Some of these concepts may be categorized as Jet Tabs, Jet Deflector Blade, Domed Deflector, Hot Gas Injection, Jetavator, Gimbal Nozzles, Liquid Injections, and JVC Systems. However, devices using these systems are generally inadequate for many current applications. Retractable Jet Vanes (Reference 7), are incompatible with the requirement for any launch canister loaded missile with stringent volume constraints as exhibited in Figure 3. Detachable Jet Tabs Systems comprising auxiliary propulsion units pivotally attached to the missile fins for coupled bi-directional motion similarly conflict with folding control surfaces and require increases in launch canister cross-section for additional volume external to the missile fuselage structure (Reference 8).

Other alternative designs also have significant drawbacks. Gimbal Nozzle Systems are heavy and complicated and are not detachable. Liquid Injection systems do not provide sufficient thrust vector angles. Existing Jet Vane Mechanisms are either nondetachable or incorporate actuation systems with feedback control electronics redundant to the missile's SCS unit. Nondetachable Jet Vane Mechanisms limit range and performance with rocket thrust degradation throughout the missile's trajectory. Self-actuation Jet Vane Mechanisms are also heavy and inherently complicated, hence, require more rocket propellant for missile launch and lack sufficient reliability. Some designs have attempted to correct some of these problems. For example, a shipboard defense system made by RMS and used on the Canadian SeaSparrow System has vanes in the missile plume. However, this system includes actuation elements that are redundant to those found in the missile's mid-body SCS, which adds unnecessary weight, complexity, and cost.

RMS Trade Studies

Figures 4 though 10 illustrate in greater detail the conceptual trade studies performed by RMS to derive the most cost effective TVC System for ESSM (Reference 9). A number of TVC candidates were conceptualized and qualitatively evaluated as illustrated in Figures 4, 5, and 6. From the original list of candidates, the conventional Jet Tab, Gimbal Nozzle, Detachable Jet Tab and JVC Systems were selected for quantitative Trade Matrix Analysis as shown in Figure 7. Figure 8 summarizes the TVC ranking indicating that the Detachable JVC concept scores technically and economically superior as well as less complex to develop and integrate. The jettisonable JVC optimizes the original structural and aerodynamic design characteristics of the missile. Actuator power application from the missile SCS to the detachable Power Take Off (PTO) Coupling Mechanism is simple and very reliable. Figure 9 exhibits the conceptual SCS and JVC coupling scheme and lists the ESSM vehicle benefits resulting from the JVC incorporating a modular design, PTO Engagement Mechanism, jettisonable feature, and roll control.

Following this evaluation, a trade-off study was performed by the RMS Vehicle Design Department to define the optimum JVC/SCS separation requirements and conceptualize candidate PTO coupling mechanisms (Reference 10). PTO coupling mechanism requirements at the SCS/JVC interface were defined as follows:

1. Maximum torque transmission capacity in clockwise and counter-clockwise directions.
2. Accommodate offset between SCS and JVC PTO shafts.
3. Decouple with vehicle bending loads applied across JVC/SCS interface.
4. Coupling mechanism outside diameter shall be no greater than 1 inch.
5. Phasing capability between SCS and JVC PTO shafts for control surface and Jet Vane alignment.
6. Geartrain backlash resulting from the PTO coupling mechanism shall be minimized.
7. Mechanism compliance shall be minimized to mitigate geartrain resonances.

8. Ease of part fabrication, minimization of manufacturing costs.
9. Limit manual manipulation of coupling mechanism during JVC/SCS mating.
10. Accommodate axial assembly tolerance stack-up between SCS and JVC at PTO shaft.

Figure 10 shows the PTO coupling mechanism trade study for sixteen different candidate concepts. All mechanism requirements were quantified with high and low scores except for the outside diameter limitation (number 4 above), which was not a discriminator since every concept met this requirement. The Cardan Coupling concept, easily integrated into the SCS/JVC Geartrain as illustrated in the Figure 11, proved the most desirable with a maximum total score of 37. The detail design effort incorporated the PTO Cardan Coupling Mechanism inside the SCS/JVC Marman Clamp interface, within the JVC length envelope specified.

Preliminary Design Optimization

A modular jettisonable JVC System was selected to provide roll control for vertical launch since it maximized missile performance and effectiveness yet allowed discarding the system after it had performed its function. Minimal complexity and low parts count result in low cost and a reliable means of accomplishing pitch-over. RMS downselected from nine to three TVC candidates and identified the JVC as the only system capable of providing the roll control necessary for missile orientation during pitch-over. Roll control will stabilize missile roll expected at launch resulting from Dorsal Fin vortex shedding and high pitch-over velocities coupling with the vehicle roll-pitch inertial product. Roll control minimizes the time to align the missile seeker antenna against close-in threats. Additional design optimization studies immediately focused on the large volume of existing data and technical literature available to initiate Jet Vane material evaluations, hardware design, and detailed analysis (Reference 11 – 23).

After a three month preliminary design effort incorporating legacy RMS and prior industry TVC technologies, the ESSM Detachable JVC evolved rapidly. The JVC is 10.00 inches in diameter and 6.14 inches long. The JVC is divided into four independent quadrants, each housing a Jet Vane Mechanism and Geartrain Assembly, all assembled onto a annulus ring structure and covered by an external skin. The rocket plume exits though a nozzle extension cone created by the annulus ring structure, and impinges upon the Jet Vanes located in the propellant stream before exiting the JVC System. Each Geartrain Assembly receives power directly from the missile SCS by a PTO Engagement Mechanism. The PTO Engagement Mechanism couples one of the four SCS control surfaces to the JVC vane aligned within the same quadrant. The SCS power actuation system for each quadrant therefore drives the control surface and coupled Jet Vane simultaneously. A Marman Clamp mechanically attaches the JVC to the aft missile structure. After the missile has achieved sufficient velocity, aerodynamic control is feasible and the JVC is no longer required. The JVC is jettisoned by activating two pyrotechnic clamp bolt cutters, allowing the Marman Clamp to radially expand and decouple the JVC from the SCS.

Figure 12 illustrates the external and internal side views of the JVC. The right hand sectional view shows the Geartrain Assembly for a single quadrant and two views of the Jet Vane Mechanism. The Jet Vanes rotate $\pm 25^{\circ}$ during deployment, yet are designed to rotate $\pm 30^{\circ}$, and experience tip-to-tip interference with the adjacent vane when the two vanes simultaneously rotate $\pm 33.5^{\circ}$. Marman Clamp interfaces required to structurally mate with the SCS and shipboard Mark 41 VLS are incorporated with the front and aft flanges respectively. Two pyrotechnic clamp bolt cutters (not shown) are at each interface. Each set of redundant bolt cutters is activated for the aft and forward Marman Clamps to radially expand and decouple the ESSM from the shipboard VLS prior to launch, as well as JVC separation from the SCS for JVC jettison after missile pitch-over.

The JVC Skin with an integrally machined front Marman flange slides over the Inner Ring Housing Assembly and is fastened to the Inner Ring Housing. Fastening the Aft Mounting Ring to the JVC Skin to form the aft Marman flange then completes the Detachable JVC System Assembly. The JVC Skin and Aft Mounting Ring are fabricated from 2014 aluminum alloy. The exposed inner surfaces are coated for thermal protection from the rocket plume with an ablative, epoxy filled resin. The JVC Skin configuration allows the four Vane Shaft Bolts to protrude beyond the 10.0 inch outside diameter, yet retain ease of assembly, and provide vehicle weight load transfer from the forward flange to the launcher without straining the Geartrain Assembly. The Geartrain Assembly may potentially bind, and freeze the Jet Vane Mechanism from properly moving during deployment, if the tightly toleranced geartrain bearing seats creep under the constant strain of carrying the vehicle weight as the ESSM rests in the launch canister. Material creep in the Inner Ring Housing about the geartrain has been eliminated with the JVC Skin configuration.

Figure 13 exhibits the Inner Ring Housing Assembly with views looking aft and forward. The left-hand section shows the four quadrants and the geartrains positioned with respect to each Jet Vane (dashed). A conical Glass/Phenolic (Gl/Ph) Nozzle Insert is bonded inside the Inner Ring Housing for thermal insulation from the rocket plume. The right-hand section provides four views, one at each quadrant illustrating the Inner Ring Housing Assembly at different stages of construction. The port side view (9 o'clock) shows the machined Inner Ring Housing and geartrain bearing seats. The bottom view has the four gears with the bottom bearings assembled into the housing. The Starboard view (3 o'clock) shows the completed Geartrain Assembly with the Gear Mounting Plate housing the top bearings, fastened to the Inner Ring Housing, and covering the geartrain. All geartrain bearings are standard, 'off-the-shelf' purchase items. The top view shows the Jet Vane Mechanism fastened to the Inner Ring Housing, completely encapsulating the Geartrain Assembly below, and the vane Bevel Gear meshing with the geartrain Torque Transfer Gear. The Figure 14, left-hand sectional view of the PTO Pinion Gear clearly exhibits the PTO Engagement Mechanism prior to coupling with the SCS actuation system. The Figure 14, right-hand exploded view of the Cardan PTO Engagement Mechanism outlines how the two shafts couple for torque transfer. The circular adapter plate with four elliptical slots allow for shaft offset upon JVC vehicle integration, decoupling ease as the JVC is jettisoned, and minimum mechanism compliance under torsional load. The Inner Ring Housing and Gear Mounting Plates are machined from 6061 aluminum alloy. The geartrain PTO Pinion, two Idler, and Torque Transfer Gears are fabricated from case hardened, high strength AISI 9310 steel.

Figure 15 exhibits an exploded view of the Jet Vane Mechanism Assembly. Four Jet Vane Mechanisms are mounted onto a Inner Ring Housing behind the ESSM rocket nozzle. At first, Carbon/Carbon (C/C) Jet Vanes were to be externally bolted to the Vane Shaft with ten A286 CRES inserts and screws. The vane and shaft are then assembled to the Journal Block Housing with a Belleville Spring Washer, Bevel Gear, standard industry thrust and radial needle bearings. The Vane Shafts and Bevel Gears are fabricated from case hardened, high strength AISI 9310 steel. The Journal Housings are machined from 2219 aluminum alloy and the external surfaces are coated with an ablative, epoxy filled resin for high temperature applications.

The Jet Vanes were originally envisioned to be fabricated from 3-D carbon fiber reinforced, carbon matrix composites derived from chemical vapor infiltration/deposition (CVI/CVD) processes. CVI/CVD fabricated C/C brake pads are being produced for many airliner landing gears today, hence commercial synergy is possible to minimize cost. A Rhenium metal surface was to be plated onto the C/C Jet Vanes for oxidation protection as currently applied to C/C rocket motor throat inserts, but more work was required to develop this concept. Copper Infiltrated Tungsten (CIT) was later incorporated in a multi-piece Jet Vane design to ease developmental risk, though much heavier and costly than the C/C variants, to assure program schedule compliance.

The 'off-the-shelf' thrust and radial needle bearings are utilized to transmit large vane shear and bending loads to the Journal Block Housing while simultaneously allowing the Vane Shaft to rotate freely, mitigating the possibility of Jet Vane sticking or binding. The Journal Block Housing has inherent structural strength and rigidity with the 'dual pillow block' configuration to evenly distribute vane loads for robust JVC operation. Placement of the Bevel Gear at the inertial neutral axis of the Journal Block Housing limits radial and translational strain movement, enabling consistent Jet Vane torque transfer and bevel tooth engagement with the Geartrain Assembly.

Critical Design Resolutions

As the JVC development effort transitioned from the conceptual/preliminary phase and into the ESSM EMD contract, BAe Systems Australia became the design agent responsible for developing the RMS JVC concept into a TVC design that met the requirements for operation on the ESSM vehicle. BAe Systems Australia led the TVC development, fabrication, integration, and test effort with RMS as the prime contractor for the missile. A formal design process was followed where a set of full system requirements were developed and reviewed at a Systems Requirements Review (SRR). As the ESSM TVC was further developed, the design was presented and reviewed at a Preliminary Design Review (PDR), and finally as the development approached completion the final design and development test data were reviewed at a Critical Design Review (CDR). Upon successful completion of this formal design and review process, the TVC entered into EMD production where 30 units were produced for various flight-tests (References 24 and 25).

The requirements development and flowdown process included development of both the critical mechanical and electrical interfaces. The primary electrical interface to the TVC was the explosive bolt squib line and its return path. The majority of the interface development effort was mechanical in nature. Several mechanical interfaces required definition such as the TVC to SCS, TVC to rocket motor, TVC to Mark 41 Launcher, and TVC to Mark 48 Launcher. The

interface details were controlled using Interface Control Drawings that were continually updated and formally controlled throughout the design process. The critical TVC to SCS interface details included the Marman Clamp groove, alignment key, explosive bolt electrical connector, PTO shafts, and rear reference antenna waveguide. The TVC to rocket motor critical interface included the extension of the rocket motor nozzle and hot gas exhaust seal. The TVC to Mark 41 Launcher critical interface included the holdback Marman Clamp groove, sealing to the exhaust gas obturator, and anti-rotation features. The TVC to Mark 48 critical interface details primarily consisted of exhaust gas obturation and insuring sufficient volume existed for the TVC system.

A 6 Degree of Freedom (6DOF) TVC simulation was developed by BAe Systems Australia for further TVC performance requirements definition. The simulation could be implemented in three modes, TVC stand alone, SCS and TVC, or fully integrated with the ESSM vehicle 6DOF. The model was also used by BAe Systems Australia for design and development of the POM control algorithms and included equations of motion, gear train stiffness, backlash, damping, stiction, Coulomb friction, viscous friction, Jet Vane forces and moments. The initial analysis included data from previous documented studies and used theoretical methods for estimating Jet Vane loads. The data was empirically adjusted based on ESSM exhaust flow characteristics. Isentropic Supersonic Flow Theory (Linear Mach Theory) was used to compute the 2-D pressure distribution and integrated to obtain the vane forces and moments. The simulation was later verified and validated against test data gathered during TVC development tests such as cold flow, Ballistic Evaluation Motor (BEM) firings, Propulsion Section Development (PSDEV) firings, and Control Test Vehicle (CTV) test firings.

Cold flow testing was conducted at Naval Weapon Center (NWC), China Lake where supersonic airflow was used in lieu of actual rocket motor exhaust to obtain preliminary TVC performance characteristics (Reference 26). This enabled data to be obtained from nearly an unlimited number of firings using the same hardware. The Jet Vane cold flow testing eliminated the vane erosion, nozzle erosion and detrimental effects of heat on the test hardware. A 75% scale TVC was used in the tests. The scale of the TVC was limited by the volumetric capability of the cold flow apparatus. The cold flow nozzle exit conditions, pressure and mach number, were matched to the rocket motor nozzle to achieve dynamic similarity. In this case, the exit conditions were Mach 3.8 and fully expanded flow at 1.0 atmosphere. The vanes could be positioned at 0 degree, ±12.5 degree, and ±25 degree. A five component strain gage balance was used to measure the vane lift and drag forces as well as the vane hinge moments. The results indicated that the lift was highly linear with vane deflection, however lift was increased when an adjacent vane's trailing edge is deflected toward the vane of interest. The results of the cold flow testing were analytically adjusted to predict loads during an actual rocket motor firing and used in the 6DOF simulation to establish performance requirements early in the design phase.

As the TVC development continued toward the first rocket motor static firings, attention was focused on Jet Vane and Vane Shaft survivability. A lumped mass thermal model was used to predict the vane and shaft temperatures. The thermal model indicated that the stagnation temperature of the vane leading edge would reach approximately 4000 degrees Fahrenheit after 2 seconds and the shaft temperature would reach approximately 1550 degree Fahrenheit. During BEM firings, shaft temperatures were measured at 1200 degrees Fahrenheit. After reviewing published TVC test data, CIT (90%W, 10%Cu) was selected as the Jet Vane material and a Titanium-Zirconium-Molybdenum (TZM) alloy was chosen as the Vane Shaft material. The Vane Shaft design employed a large diameter flange to act as a hot gas shield and labyrinth seal for the bearings and housing. The Vane Shaft protrudes well up into the Jet Vane to react against the vane loads. BEM testing proved that this combination would survive for the duration of the POM, however, survivability during a restrained firing (full duration motor burn) remained to be demonstrated.

<u>TVC Hardware Development Tests</u>

Two developmental live static rocket motor firings with active TVC Systems were conducted early in the ESSM development phase to characterize TVC performance, validate the 6DOF simulations, determine Jet Vane and Nozzle Insert erosion, evaluate the Vane Shaft hot gas dynamic seals, and evaluate the Marman Clamp Release Mechanism with explosive bolts. These development tests were complete end-to-end ground based tests conducted at NAMMO Raufoss, Norway with the participation of BAe Systems Australia as TVC lead, Allied Signal Canada as SCS lead, and RMS as the missile prime contractor.

The rocket motors were flight ready, dual solid propellant rocket motors provided by NAMMO Raufoss. The Allied Signal Canada developed, fully operational, form factored SCS was provided and was

driven by an external test bay similarly developed by Allied Signal Canada, to provide the Jet Vane position commands as well as the TVC jettison command. The external test bay also recorded telemetry such as Jet Vane position, SCS drive motor current, SCS battery voltage, and thermocouple data. BAe Systems Australia provided their final design prototype TVC and live Marman Clamp Release Mechanism. Significant system integration and test activities were conducted including numerous dry runs and pre-live runs so as to insure proper system operation and minimize risk during the actual firing.

The first static firing was conducted at low temperature. The entire rocket motor, SCS, and TVC assembly or Kinetic Upgrade Package was soaked at –25 degrees Celsius for 24 hours. The Kinetic Upgrade Package was then transferred into the rocket motor test bay and integrated onto the rocket motor test stand with multi-component force measuring instruments. The loads from the test stand were resolved into thrust, side loads, and TVC turning moments or equivalent thrust vector angle. The side force data as a percentage of thrust is shown in Figure 16. During the first static firing the TVC was successfully jettisoned after 4.0 seconds. The TVC was recovered and fully analyzed against the test objectives. The Jet Vane side loads and drag were well within the expected values as were the Jet Vane and Nozzle Insert erosion characteristics. The Vane Shaft hot gas seals performed flawlessly by preventing the hot gas and exhaust particulates from contaminating the shaft bearings. The explosive bolt and Marman Clamp Release Mechanism successfully jettisoned the TVC and the Cardan PTO couplings disengaged properly without binding or causing TVC tip-off. The test was a complete success meeting all primary, secondary, and tertiary objectives.

A second developmental live static firing was conducted at high temperature. This time the entire Kinetic Upgrade Package was soaked at +65 degrees Celsius. The TVC was successfully jettisoned after 7.0 seconds. Although holding onto the TVC for 7 seconds before jettisoning is twice as long as the maximum expected POM duration, valuable data was gained on Jet Vane and Nozzle Insert erosion for the upcoming full burn, Restrained Firing Tests. Again, the TVC was recovered and analyzed against the test objectives. The test was considered a complete success.

Prior to conducting a developmental missile flight test on a missile test range, certain critical parameters must be demonstrated so as to minimize risk from a safety standpoint. Missile control during the initial stages of the flight is one such parameter. Therefore, a Preliminary Flight Rating Test (PFRT) was required of the ESSM TVC System prior to conducting the first vertically launched, Control Test Vehicle (CTV) flight designated CTV-3. The PFRT test is a ground based static test firing with active TVC similar to the two previous developmental static firings. The PFRT test was conducted at NAMMO Raufoss, Norway and included the same participants as at the developmental firings. The PFRT test was conducted at high temperature (+65 degrees Celsius). The test was a complete success and allowed the ESSM program to embark on the missile flight test program (References 27 and 28)

Since the ESSM TVC was being developed under an EMD program and was destined for production, the TVC System required qualification. The qualification plan required subjecting the TVC to the environments specified in Critical Item Development Specification (CIDS). This included non-operating environments such as transportation vibration, handling shock, high impact shipboard shock, shipboard vibration, high temperature storage, low temperature storage, temperature shock, altitude, rain, sand and dust, washdown, fluid contamination, and humidity. The TVC was also subjected to operating environments such as low temperature, high temperature, free flight vibration, and launch shock. Two rocket motor static test firings with active TVC Systems were also conducted in a similar manner to the previous static firings. The first qualification test was conducted at low temperature (-25 degrees Celsius) while the second test was conducted at high temperature (+65 degrees Celsius). The TVC successfully passed all environmental tests as well as the two static firings.

TVC Hardware Flight Tests

The ESSM EMD contract required the testing of Restrained Firing Vehicles (RFVs) to verify the restrained firing capabilities of the Mark 29, Mark 41 and Mark 48 launchers (Reference 29). Three RFVs were required, one for each type of launcher. The TVC System is not used on a Mark 29 configured missile since the legacy launcher is trainable onto incoming targets. The objectives of the restrained firings were to:

1. Verify that an ESSM can safely survive a restrained firing.
2. Verify the Mark 41 VLS and Mark 25 Quadpack Canister can safely restrain the vehicle.
3. Verify the Mark 48 Guided Missile Vertical Launching System (GMVLS) with the modified Mark 20 Canister can safely restrain the missile.

4. The rocket motor exhaust gases are safely vented.
5. Missile pyrotechnic explosives do not ignite.
6. The Exhaust Control System (ECS) can withstand the environment of a restrained firing.

The TVC CIDS required that the explosive bolts used on the TVC Marman Clamp withstand a temperature of 205 degrees Celsius (400 degrees Fahrenheit) without detonation. The Mark 41 launcher Mechanical Interface Control Document (MICD) specified that the missile shall remain intact during and after a restrained firing condition. Although not a requirement, a goal of the TVC design was to ensure that the Jet Vanes degrade gracefully so as not to damage the launcher by allowing large pieces to be propelled down through the plenum. Also, in the case of a Mark 41 configured missile, the TVC airframe structure provides the direct load path for restraining the entire round. Failure of the TVC airframe structure during a restrained firing could allow the missile to egress the launcher and create a significant safety hazard. In the case of a Mark 48 restrained firing, it is considered acceptable for the TVC to separate from the missile after rocket motor burnout. The Mark 48 configured ESSM is a rail launched missile restrained within the launcher with Hooks and Lugs fastened to the top of the rocket motor.

The ESSM round designated as RFV-2 was a Mark 48 configured missile complete with a flight configured rocket motor and TVC System. The SCS was a non-functioning unit, therefore, the Jet Vanes remained fixed at zero degrees during the firing. The rocket motor was instrumented with a pressure transducer to verify a nominal rocket motor burn. The respective International team members provided the missile components. RMS conducted the missile final assembly and acceptance tests. The round was fired at the Naval Air Warfare Center (NAWC), Weapons Division, White Sands Missile Range (WSMR) in New Mexico. Upon completion of the test, the missile was decanned from the launcher and fully analyzed against the test objectives. The test was considered a complete success. The Jet Vane Mechanisms remained intact and secure in the TVC Housing Assembly. The Gl/Ph Nozzle Insert did not erode through and protected the TVC airframe structure. However, several seconds after the end of the rocket motor burn, an explosive bolt that secures the TVC to the SCS cooked off as a result of the extreme temperatures generated in the launcher exhaust gas management system. The deterioration of the explosive bolt allowed for the TVC to drop from the missile and down into the launcher exhaust plenum. This was considered to be acceptable since it did not occur during the motor burn and the launcher was not damaged.

The ESSM round designated as RFV-3 was a Mark 41 configured missile complete with a full burn, flight rocket motor and TVC System similar to RFV-2. Again, the rocket motor was instrumented with a pressure transducer and was fired at WSMR. This test was crucial as the TVC airframe structure provided the load path for restraining the entire missile. Upon completion of the test, the missile was removed from the launcher and fully analyzed against the test objectives. One Jet Vane and partial Vane Shaft assembly eroded away and was propelled into the launcher exhaust gas plenum during the test. The launcher was not damaged and the missile was successfully restrained. The Jet Vane Mechanism erosion was attributed to the unique geometry of the Mark 25 Quadpack canister and resultant exhaust gas flow field. Upon review of the test hardware the test was considered a success.

The ESSM EMD contract required the firing of Blast Test Vehicles (BTVs) to verify launcher separation, canister mechanical performance, and gas management (Reference 30). The BTVs flew ballistic trajectories and did not have an active SCS, autopilot or Guidance Section. Two BTVs were required, one for a Mark 48 launcher and one for a Ship Defense Launching System (SDLS) which comprised a Mark 25 Quadback Canister and Mark 41 VLS. Since these were both vertical launchers, both missiles had TVC Systems. The objectives of the BTV firings were to:

1. Demonstrate proper missile egress from the Mark 25 Quadpack Canister/ SDLS.
2. Evaluate SDLS-to-missile communications and Launcher Control System functions.
3. Demonstrate proper Mark 25 Quadpack Canister explosive bolt, Marman Clamp Release Mechanism, launch rail and fly-through cover performance.
4. Evaluate the Mark 25 Quadpack Canister and interface seals.
5. Quantify ablative erosion and Quadpack Canister environmental effects.
6. Verify the launcher cells can withstand the effects of an ESSM launch with only minor restoration required.
7. Verify the launch rail, holdback latch and other launcher mechanical interfaces to the ESSM function as designed.

The TVC CIDS also required that the TVC provide a missile anti-rotation feature for the Mark 41 configured round during launcher egress.

The ESSM rounds were designated as BTV-2 and BTV-3. The BTV-2 round was a Mark 48 configured missile while the BTV-3 round was configured as a Mark 41. Each were complete with a flight configured short burn rocket motor and TVC System. The short burn rocket motor had the exact thrust and thermal characteristics as the flight motor, but with a reduced burn time. The SCS was a non-functioning unit, therefore, the Jet Vanes remained fixed at zero degrees during the flight. Again, the rocket motor was instrumented with a pressure transducer. The missile final assembly and acceptance tests were conducted by RMS. The Mark 48 configured round was fired at WSMR while the Mark 41 configured round was fired at Naval Sea Warfare Center (NSWC), Dahlgren Virginia. The TVC Systems performed perfectly throughout the tests, achieved all objectives and were considered a complete success.

The ESSM EMD contract required CTV flight tests to verify the kinematic capability and aerodynamic control of the ESSM missile with pre-programmed control maneuvers (Reference 31). The objectives of the CTV firings were to:

1. Collect structural and thermodynamic environmental data
    a. Flight vibration
    b. Flight stress loads
    c. Body modes
    d. Aerodynamic heating
2. Characterize airframe and autopilot performance
    a. Validate digital autopilot time constant and stability
    b. Determine induced roll-yaw moments
    c. Determine aerodynamic drag affect
    d. Validate roll control
3. Verify missile software
    a. Validate Inertial Reference Unit (IRU) software
    b. Validate digital autopilot software, launch modes, aerodynamic control
4. Characterize propulsion performance and velocity time history
5. Verify POM algorithm and software

Two vertically launched CTV missiles were flown from the Mark 41 VLS at WSMR and were designated as CTV-3 and CTV-4. Both the CTV-3 and CTV-4 vehicles were required to perform a POM using the TVC, then jettison the TVC on completion of the POM.

Since CTV-3 was the first missile to perform a POM using the TVC, a relatively mild POM was executed. The vehicle was required to fly vertically for 25 yards to clear the ship, then pitched over from vertical to a 40 degree flight path angle (40 degrees above the horizon). During the POM, the vehicle remained roll stabilized and achieved a maximum angle of attack. The actual Jet Vane deflection as a function of time is shown in Figure 17. At 2.9 seconds the POM was complete (i.e. the missile body rates were stabilized within the pre-determined values) and the TVC was successfully jettisoned and control was transferred from the transition autopilot to the midcourse/terminal autopilot. Post flight analysis of telemetry and radar data as well as high-speed film indicated that the TVC performed perfectly.

CTV-4 executed a near maximum POM achieving a zero degree (horizontal) flight path angle. The launcher, instead of being vertically oriented, was angled 20 degrees up range (i.e. away from the direction of flight) and simultaneously angled cross range. This represented a launch scenario where the ship has rolled 20 degrees away from the target and is pitching. Once again the missile flew straight out of the launcher for 25 yards to clear the ship, then executed a roll maneuver to orient itself with the flight path, and then pitched over to the zero flight path angle. During the POM the vehicle remained roll stabilized and achieved a maximum angle of attack of 90 degrees. The actual Jet Vane deflection as a function of time is shown in Figure 18. At 2.9 seconds the POM was complete, however, the TVC was not jettisoned due to a failure in the SCS explosive bolt firing circuitry. Figures 19, 20, and 21 depicts the CTV-4 Flight from canister egress, through pitch over, to horizontal missile fly out respectively.

<u>Summary and Conclusion</u>

The Detachable JVC System has been successfully developed to satisfy the very stringent ESSM TVC requirements. The primary value of the TVC to ESSM is to enable an effective POM immediately after vertical shipboard launch by generating steering forces normal to vehicle flight and eliminating roll instability. The minimization of parasitic weight, limited thrust degradation, and aerodynamic optimization of the missile design furthermore enhance the interception of fast, low flying targets at extended ranges by jettisoning the TVC after pitch-over.

The novelty of the JVC concept is in developing a TVC system by coupling the Jet Vanes to the SCS power actuation system, and only jettisoning the passive, mechanical components. The principal advantages of the JVC concept are optimum weight

and design simplicity producing a relatively inexpensive and robust TVC system. Significant parasitic weight and TVC cost to the missile system are minimized by coupling the vane mechanism to the SCS power actuation system via the Geartrain Assembly and PTO Engagement Mechanism, and deleting the requirement for active TVC power actuator and control electronic systems. The remaining passive, mechanical TVC components can then be decoupled from the SCS and jettisoned after significant vehicle velocity is achieved for aerodynamic control to reduce missile weight, eliminate vane plume drag, and enable greater mission range and terminal velocities. Design simplicity gained by eliminating redundant TVC power actuation systems, and relying on direct drive mechanical linkages offers greater reliability and ease of vehicle system operation over previously designed pneumatic, or autonomously powered JVC Systems.

Future RMS applications are expected in existing missile programs for product evolutions into areas such as multiple mission capabilities. The JVC concept provides an inexpensive, disposable mechanism for retrofitting high speed, air-to-air missiles for low speed surface launches with TVC. A US Patent was published in 1998 for the ESSM JVC, as well as a number of foreign filings were issued in NATO and other Allied countries worldwide (Reference 32).

Acknowledgment

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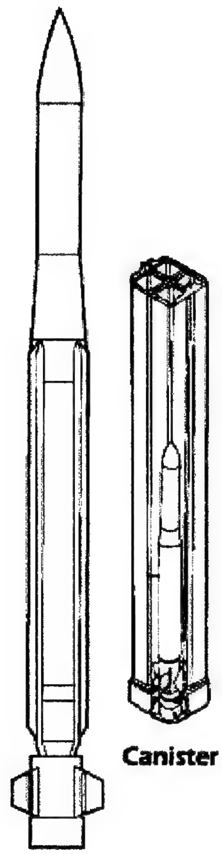

ESSM Technical Data	
Length	145.5"
Diameter	8" and 10"
Weight	615 lbs
Speed	Supersonic
Warhead	Blast Fragment
Motor	Dual Propellant
Navigation	Proportional Navigation
Midcourse Guidance	Inertial/Command
Terminal	Home All the Way, Sample Data Homing

Figure 1 - ESSM Mark 41 VLS Configuration and Technical Data

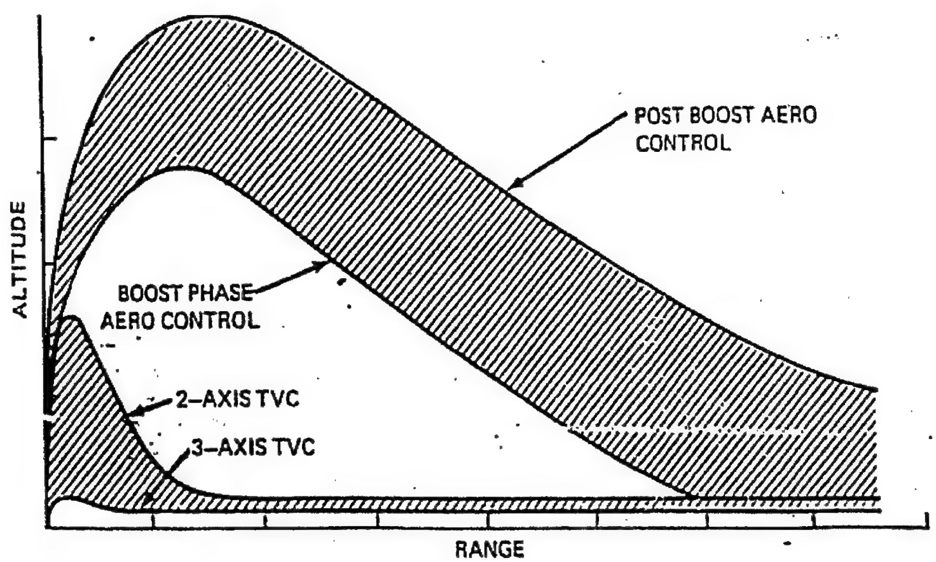

Figure 2 – Vertical Launch Trajectories Against Low Altitude Targets

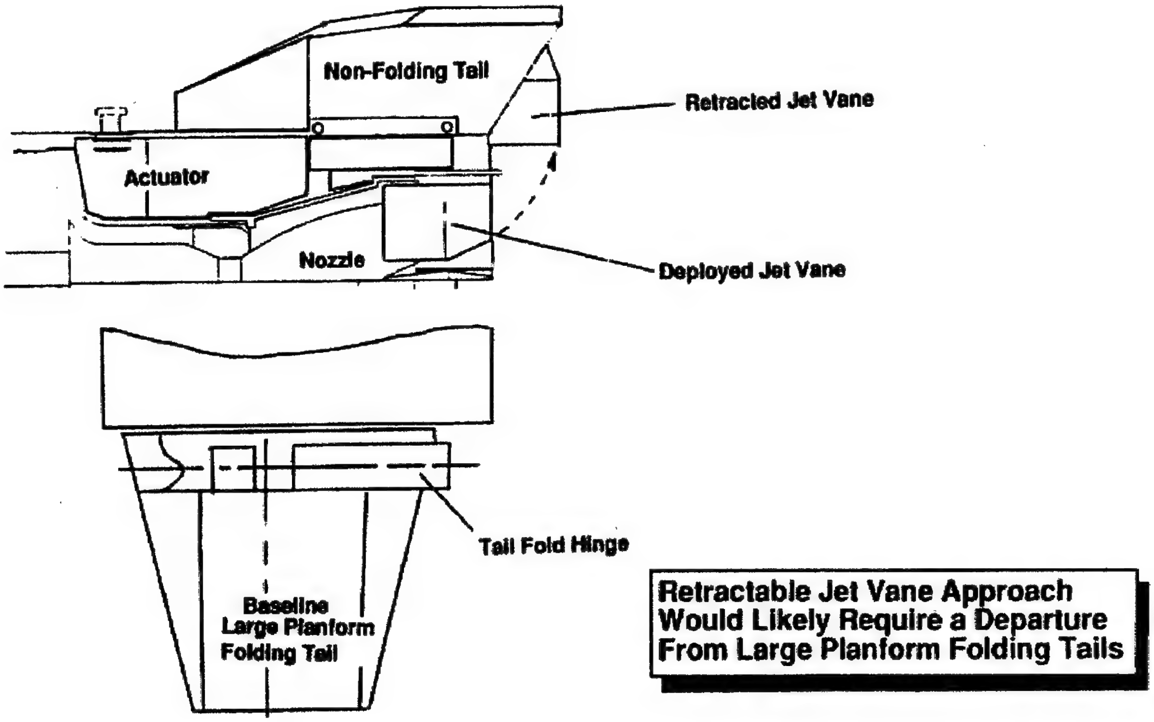

Figure 3 – Retractable Jet Vane Incompatibility to ESSM

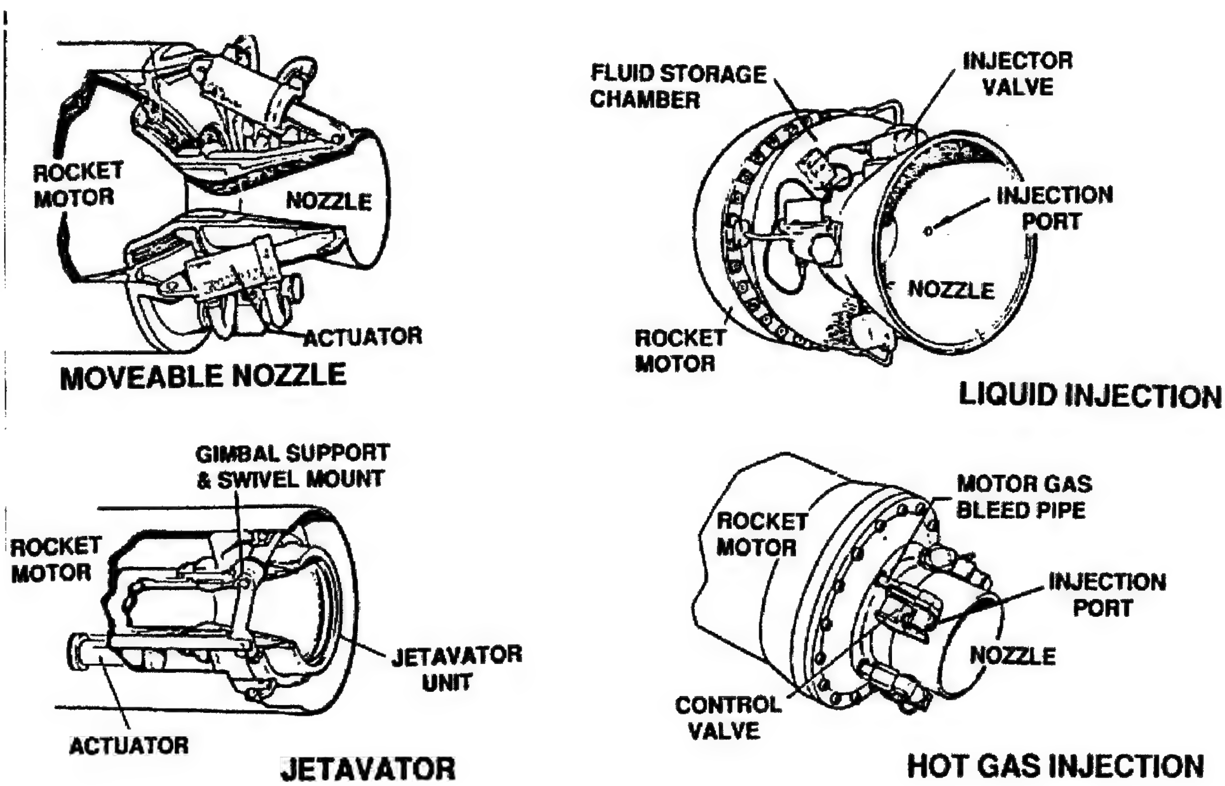

Figure 4 – TVC Candidates

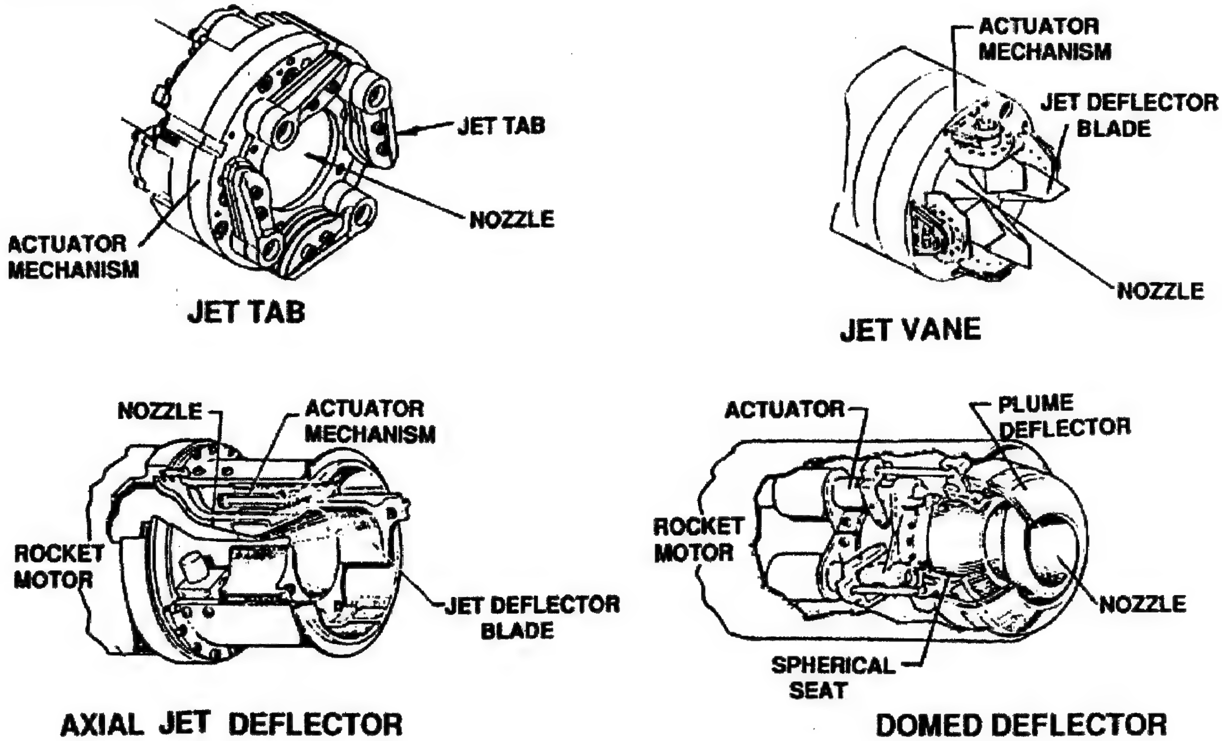

Figure 5 – TVC Candidates

Candidate	Thrust Vector Angle	Remarks
Flex Seal Moveable Nozzle	15°	Selected for Further Study
Trapped Ball Moveable Nozzle	20°	Selected for Further Study
Liquid Injection	4°	Insufficient TVA
Hot Gas Injection	12°	Valve Development Risks
Jetavator	30°	Packaging Difficulties
Axial Jet Deflector	7°	Insufficient TVA
Jet Tab	10°	Selected for Further Study
Domed Deflector	18°	Packaging/Sealing Difficulties
Jet Vane	10°	Selected for Further Study

Moveable Nozzle, Jet Tab and Jet Vane Candidates Selected for Further Study

Figure 6 – TVC System Trade Study, Nine Candidates were Compared and Evaluated

	ROLL CONTROL?	ADDITIONAL SERVOS REQUIRED	EXHAUST PLUME SURVIVABILITY RISK?	THRUST DEGRADATION	JETTISONABLE?	MODULAR AT ROUND LEVEL?	RESTRAINED FIRE DEBRIS RISK?	LAUNCH WEIGHT (LBS)	POST PITCHOVER WEIGHT (LBS)	ADDITIONAL LENGTH REQ'D TO IMPLEMENT TVC (INCHES)	*ASSEMBLE-ABILITY (SAFETY)	TVC BLENDING WITH TAILS
MOVEABLE NOZZLE	NO	2	NO	COSINE ONLY	NO	NO	NO	62	62	3.5 ELX	POOR	GOOD
POWER TAKE OFF JET VANE	YES	0	YES	11%*	YES	YES	YES	54	36	5.5 VANE MECHANISM	GOOD	GOOD
JET TAB	NO	4	YES	1% PER°	NO	NO	YES	72	72	2.2 TABS 2.9 ELX	FAIR	GOOD
POWER TAKE OFF JET TAB	NO	0	YES	1% PER*	YES	YES	YES	66	36	2.2 TABS 2.5 MECH	FAIR	FAIR
SERVO JET TAB	NO	4	YES	1% PER°	YES	YES	YES	72	36	2.2 TABS 4.0 ACT	FAIR	GOOD

*AVERAGE DURING PITCHOVER

Figure 7 – TVC Concept Downselection Trade Study Matrix

Candidate	Technical	Cost	Risk
Jet Vane	3.81	3.3	3.67
Jet Tab	2.46	1.67	2.58
Moveable Nozzle	3.81	2.5	2.42

Key:

5 = Good
4
3
2
1 = Poor

JET VANE TVC IS THE PREFERRED APPROACH

Participating Disciplines

- Propulsion
- Flight Dynamics
- Design
- Configuration Mgmt
- Thermodynamics
- Program Mgmt

Figure 8 – ESSM Final TVC Candidate Ranking and Scoring

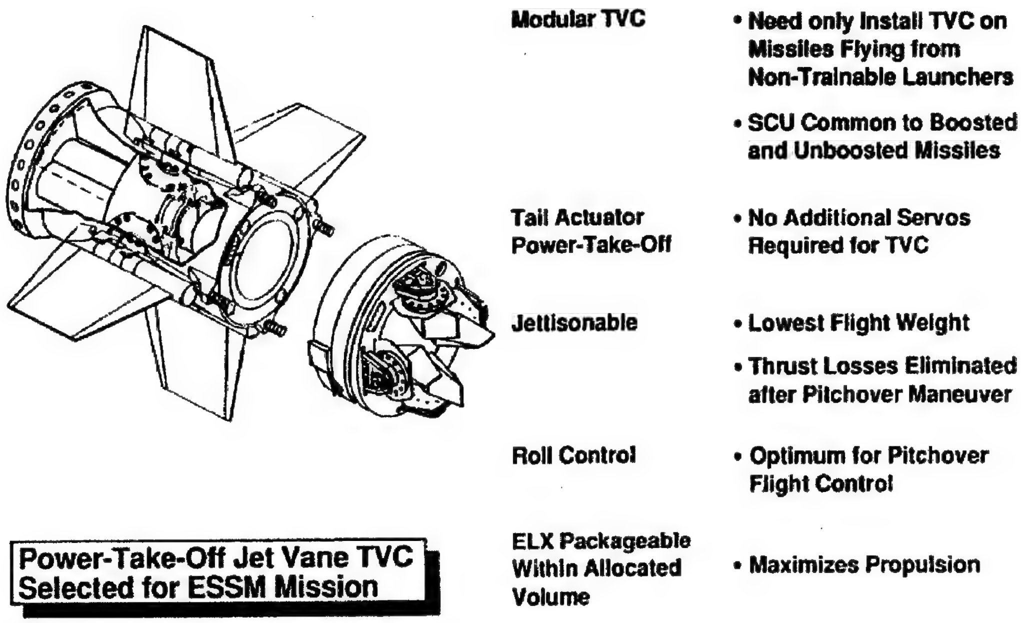

Figure 9 – ESSM Jet Vane TVC Downselection and Conceptualization

REQUIREMENTS / Score 1-5: 5=high 1=low / CANDIDATES	125# IN TORQUE	SHAFT OFFSET	DECOUPLING	SHAFT PHASING	MIN BACKLASH	MIN COMPLIANCE	SIMPLE FAB	AUTO MATING	AXIAL STACKUP	TOTAL SCORE
Tapered Spline	5	1	3	3	1	4	2	2	1	22
AMRAAM Wing Joint	5	1	3	3	4	4	1	3	4	28
Tapered Ball Slot	5	1	3	3	4	4	1	1	1	23
Ball Slot CVJ	5	1	3	3	4	4	2	1	3	26
Ball Slot Coupling	5	1	5	3	3	2	3	1	1	24
Double Capstan	5	4	2	4	2	1	4	1	4	27
Flex Tongue & Groove	4	5	5	1	5	1	3	2	2	28
Tongue & Groove	3	1	5	3	4	2	2	1	5	26
Cardan Coupling	5	5	5	4	4	5	2	2	5	37
Spline Coupling	5	1	1	4	5	5	4	3	5	33
3 Jaw/Spider	5	3	4	2	1	4	5	3	5	32
Bevel/Thread Socket	5	1	5	4	5	5	1	3	4	33
Bevel/Spring Socket	2	1	5	4	5	1	1	4	5	28
Extended Pinion	5	1	1	3	5	5	5	5	5	35
X-Face	5	1	5	2	4	5	5	3	5	35
Double Spline	5	1	4	3	2	5	5	4	5	34

Figure 10 – PTO Shaft Couple Mechanism Trade-Off Study

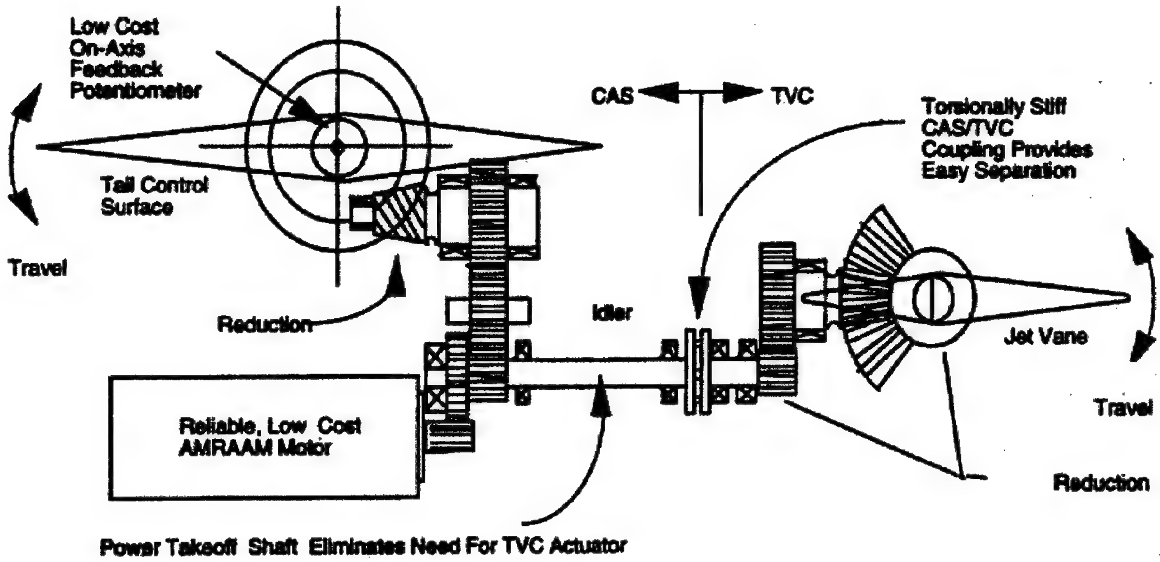

Figure 11 – Cardan PTO Coupling Mechanism and SCS/JVC Geartrain

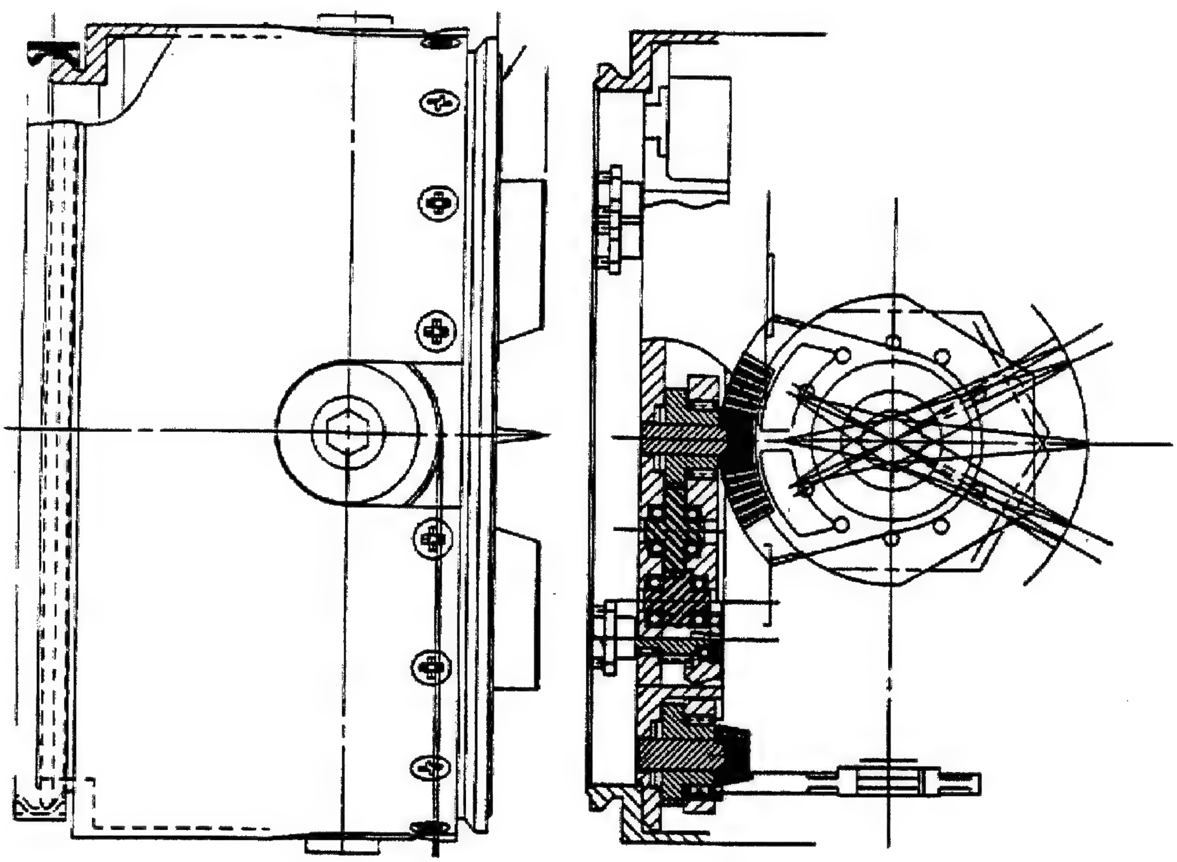

Figure 12 – Detachable JVC System, Side Views

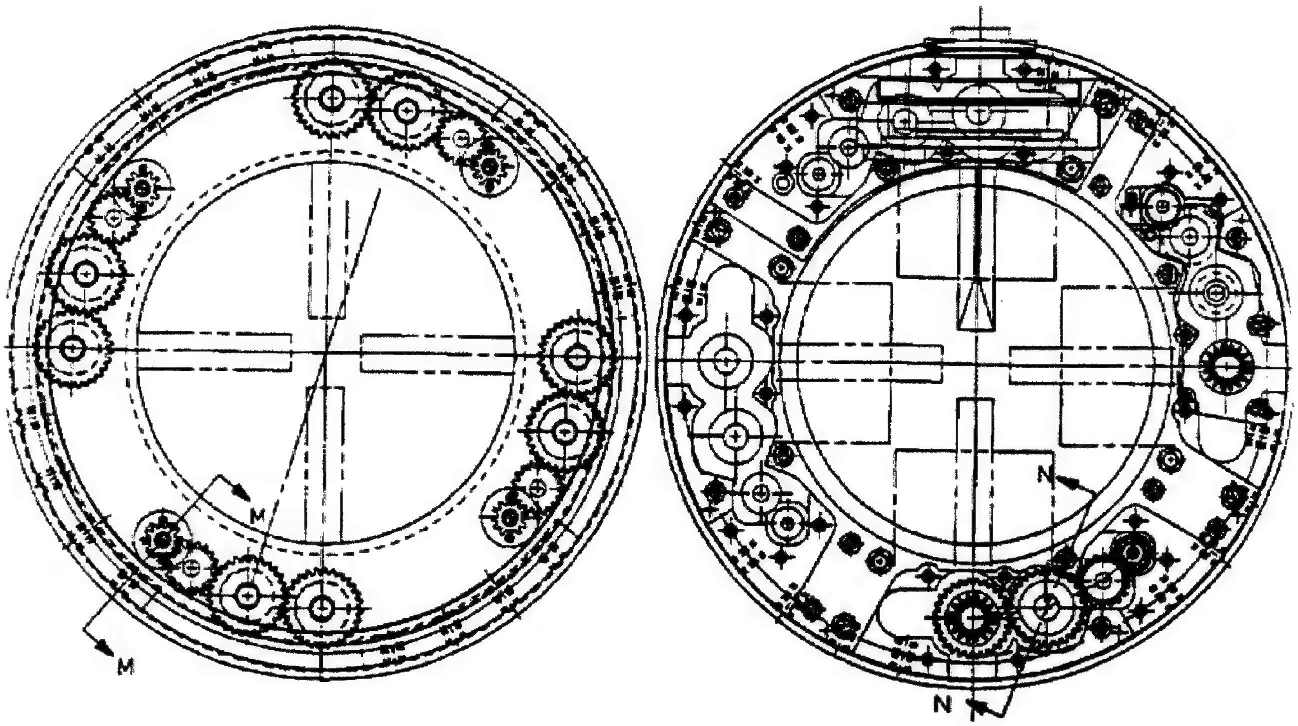

Figure 13 – Detachable JVC System, Aft and Forward Looking Views

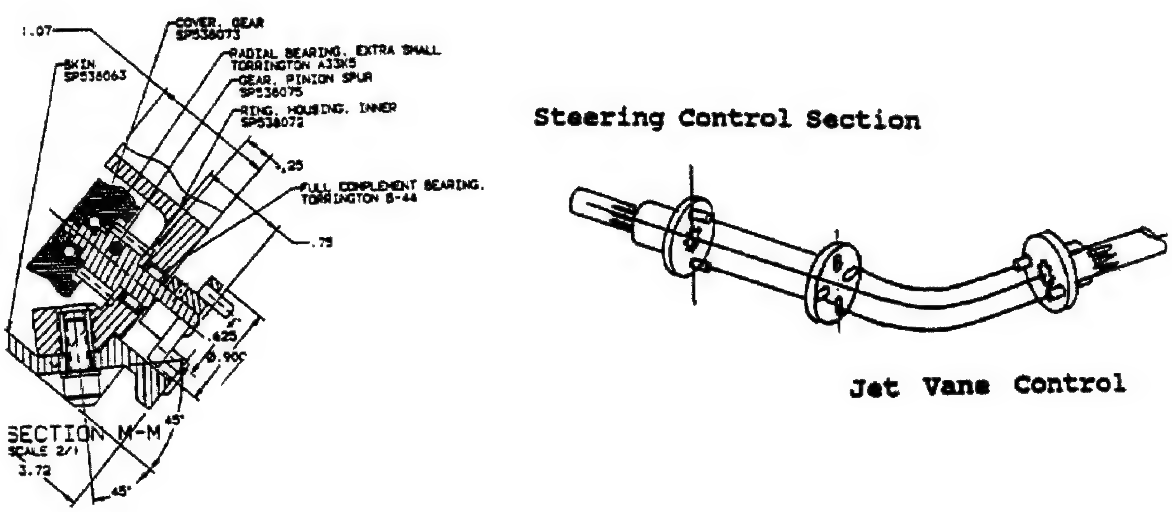

Figure 14 – PTO Engagement Mechanism

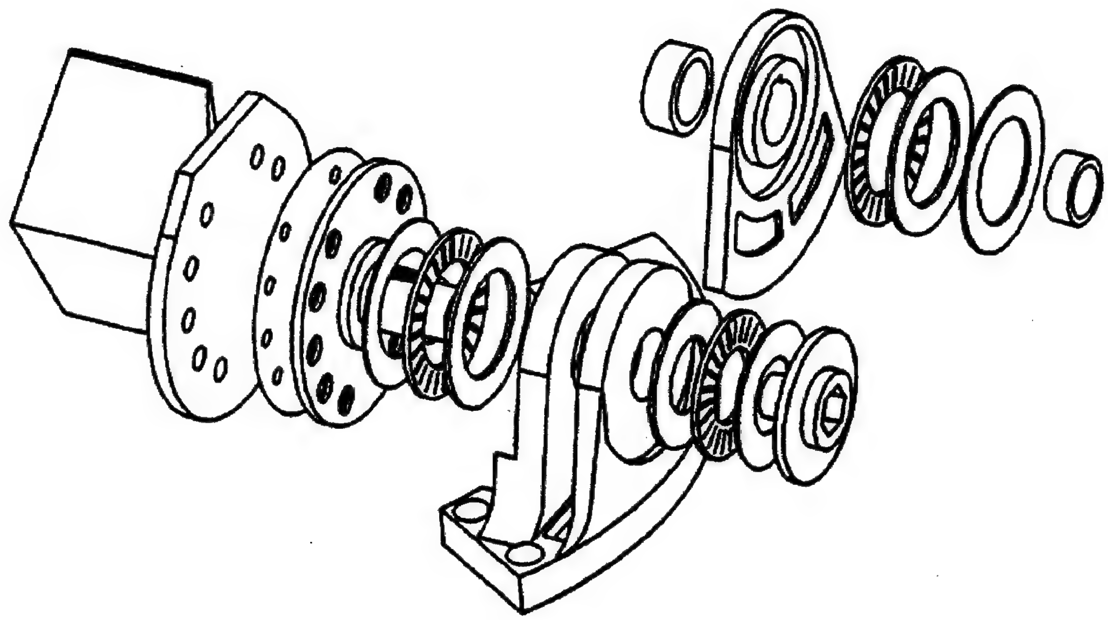

Figure 15 – JVC Vane Mechanism, Exploded View

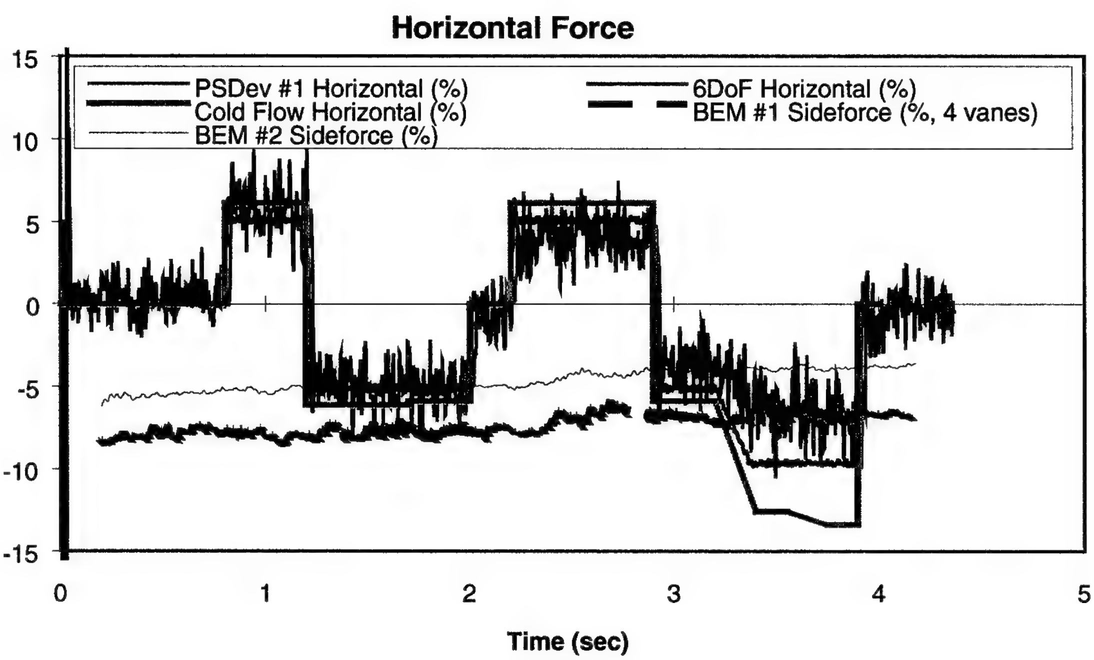

Figure 16 – TVC Horizontal Force as a Percentage of Thrust

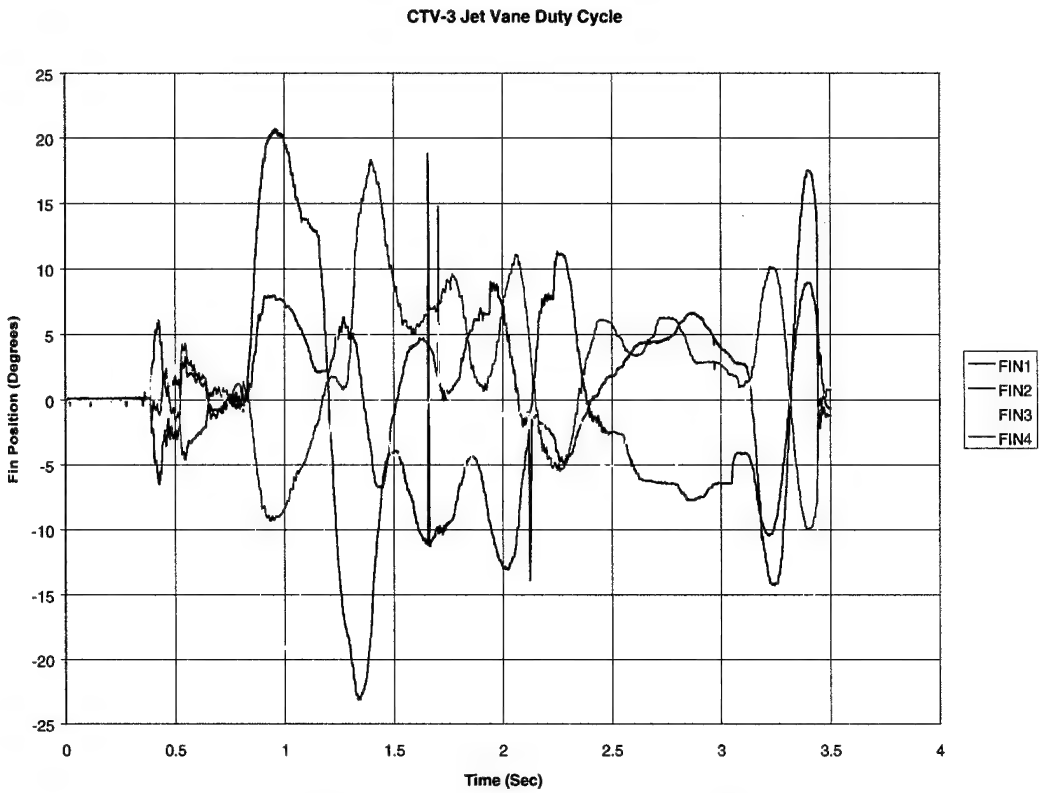

Figure 17 – CTV-3 Jet Vane Duty Cycle

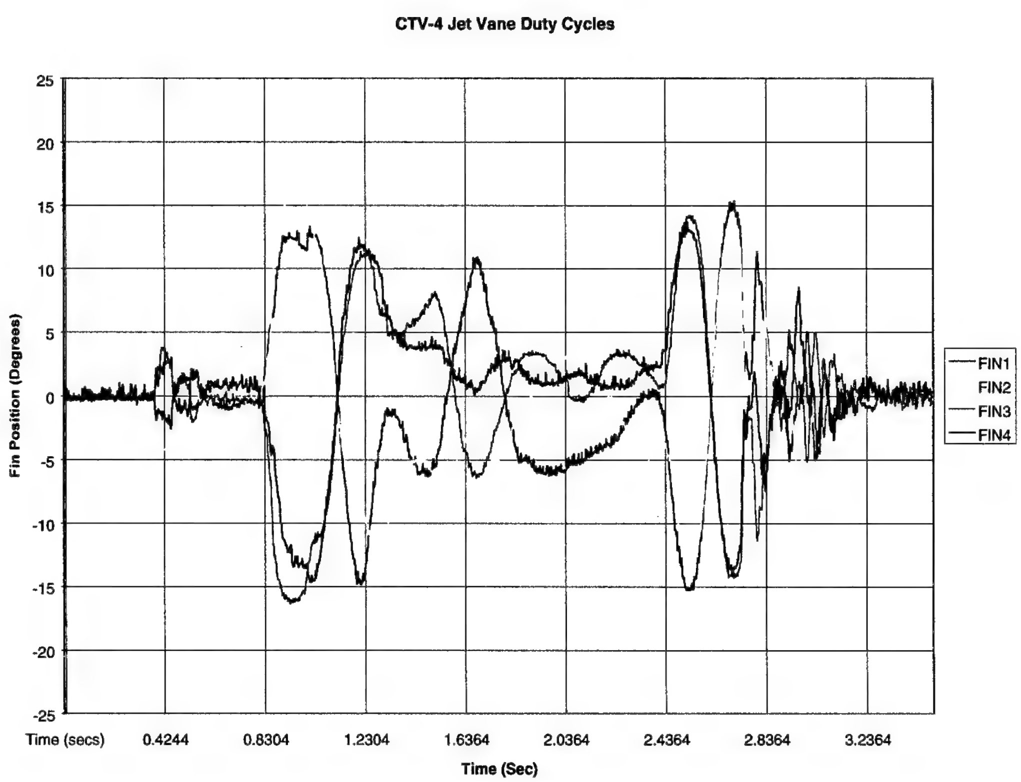

Figure 18 – CTV-4 Jet Vane Duty Cycle

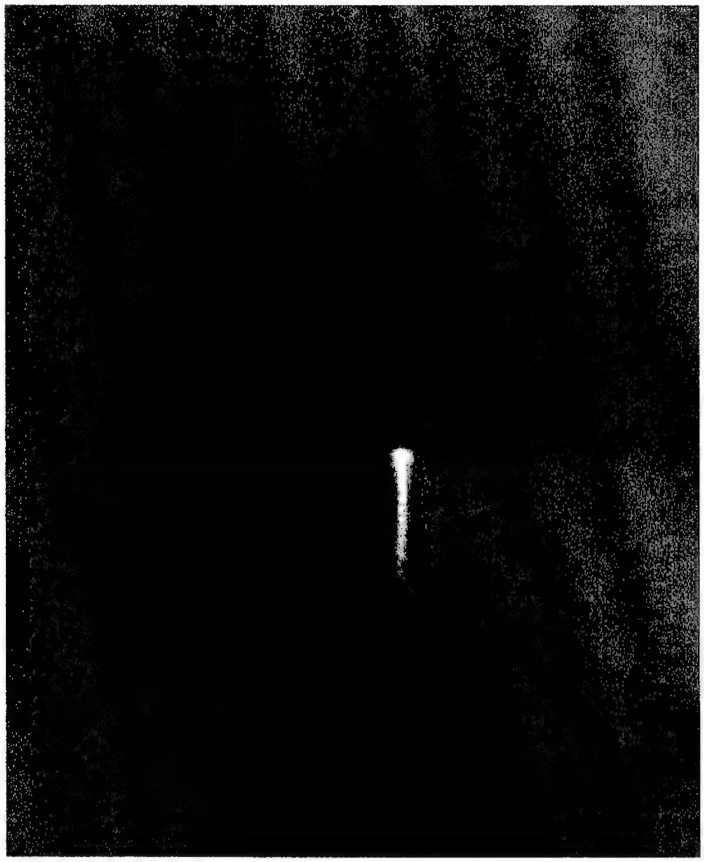

Figure 19 – CTV-4 Flight, Canister Egress

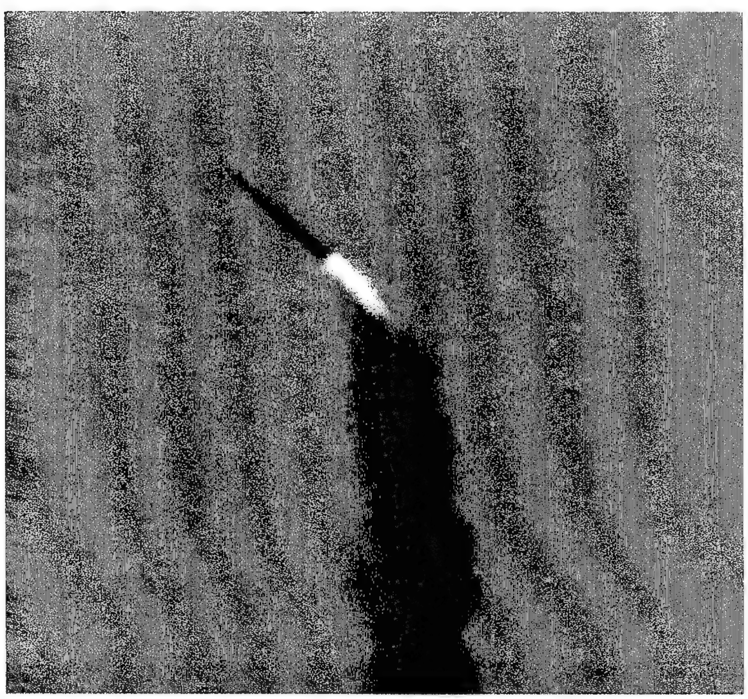

Figure 20 – CTV-4 Flight, Initial Pitch Over Maneuver (POM)

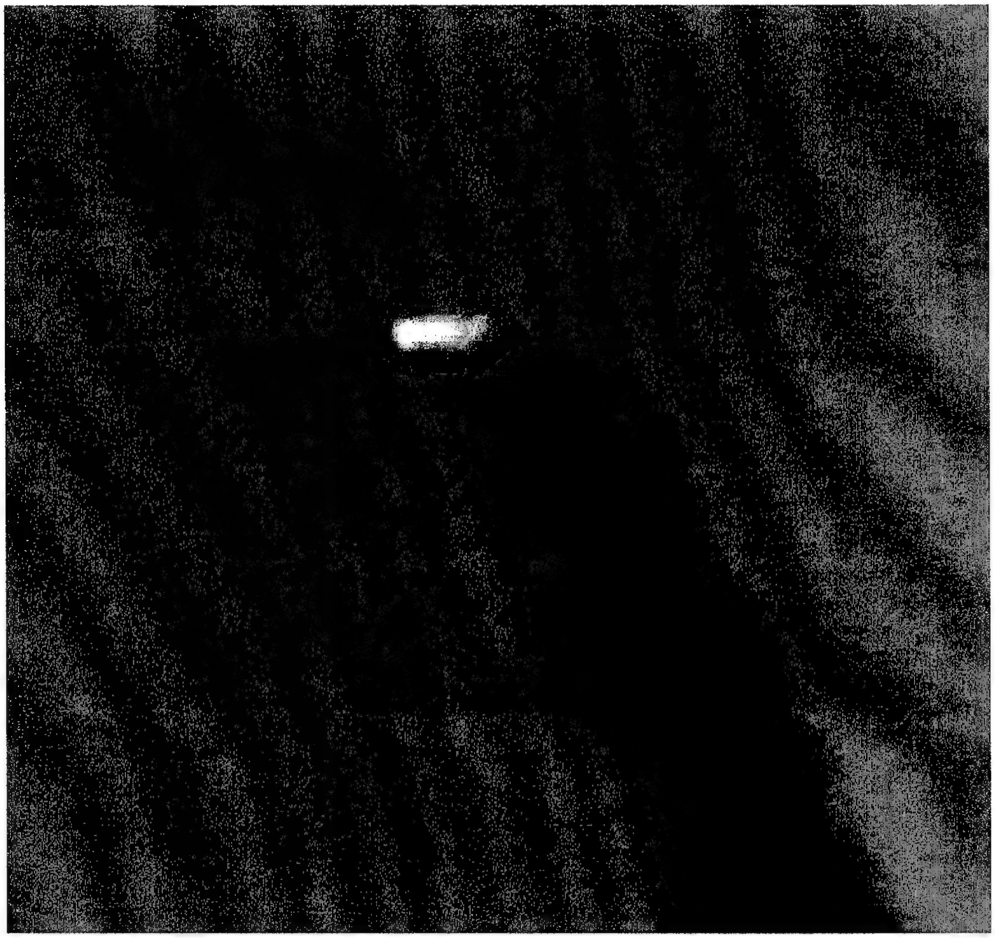

Figure 21 – CTV-4 Flight, POM Completion and Horizontal Missile Fly Out

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Raytheon
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Subj: ~~Jet Vane Control System Prototype hardware Development for ESSM~~

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f. They are not themself debarred, suspended, or otherwise ineligible to perform on U.S. or Canadian Government contracts, and have not violated U.S. or contravened Canadian export control laws, and have not had a certification revoked under the provisions of U.S. DoDD 5230.25 or Canada's TDCR.

6. CONTRACTOR CERTIFICATION

I certify that the information and certifications made by me are true, complete, and accurate to the best of my knowledge and belief and are made in good faith. I understand that a knowing and willful false statement on this form can be punished by fine or imprisonment or both. *(For U.S. contractors see U.S. Code, Title 18, Section 1001 and for Canadian contractors see Section 26 of the Defense Production Act.)*

a. TYPED NAME *(LAST, First, Middle Initial)*	b. TITLE	c. SIGNATURE	d. DATE SIGNED
Plumer, Daniel L.	Manager		

7. CERTIFICATION ACTION *(X one)*

X a. CERTIFICATION ACCEPTED. This certification number, along with a statement of intended data use, must be included with each request for militarily critical technical data. NUMBER 0001182

b. RETURNED. Insufficient information:

c. REJECTED. Does not meet eligibility requirements of DoDD 5230.25 or of Canada's TDCR.

8. DOD OFFICIAL

a. TYPED NAME *(LAST, First, Middle Initial)* McClenahan, Joseph. M.

b. TITLE U.S. Representative
United States/Canada Joint Certification Office

c. SIGNATURE

d. DATE SIGNED JUN 18 1998

9. CANADIAN OFFICIAL

a. TYPED NAME *(LAST, First, Middle Initial)* Davidson, Robert H.

b. TITLE Canadian Representative
United States/Canada Joint Certification Office

c. SIGNATURE

d. DATE SIGNED JUN 18 1998